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Optimization of HFMI/PIT Parameters with Simultaneous Multiple Response Consideration using Multi-Objective Taguchi Method for Fatigue Life Enhancement of Friction Stir Welding

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Abstract

The friction stir welding process is witnessing a growth in its application in a wide range of The friction stir welding (FSW) process is witnessing a growth in a wide range of industrial applications due the minimal governing parameters and many other advantages as a solid state welding compared to the commonly used fusion welding process. However, tensile residual stress remains to be significant concern due to its extensive clamping and stirring process which can lead to lower fatigue resistance particularly in structures subjected to fluctuating loads. Up to day, research dealing with fatigue enhancements methods for FSW is rarely found in literature. This novel study presents an unconventional method to optimize the governing process parameters of Pneumatic Impact Treatment (PIT) also known as one of the High Frequency Mechanical Impact (HFMI) techniques. The post weld treatment is aimed to enhance fatigue resistance of FSW butt joints. The experimental study was conducted for Aluminum alloy (AA 6061) plates with thickness of 6 mm under varied PIT parameters centered on the intender pin diameter, applied air pressure and hammering frequency. The investigation began with obtaining optimum parameters for single response by using conventional Taguchi method with L9 orthogonal array. Further, advanced optimization approach by means of Multi-objective Taguchi Method (MTM) attempts to consider the multiple quality features simultaneously which are hardness value and fatigue life cycle. The significant level of the PIT parameters was investigated by using analysis of variance (ANOVA). As the final results, the optimum value was acquired by calculating the total normalized quality loss (TNQL) and multi signal to noise ratio (MSNR). Subsequent confirmation test was conducted upon determination of the optimized PIT parameters.

Keywords: *Friction stir welding, 6061, Optimization, Taguchi Method, High Frequency Mechanical Impact (HFMI), Pneumatic Impact Treatment (PIT), Fatigue*

1. Introduction

Friction stir welding is a widely used alternative to the conventionally used fusion welding process for joining aluminum alloys due to its favorable conditions over the later. It is accepted in many industries requiring lightweight high strength materials for possessing favorable conditions such as improved mechanical properties, less shrinkage and distortion as well minimal stress concentration. Although this solid state process induces lesser tensile residual stress than the normally used fusion welding process, fixed and rigid clamping magnitudes a significant amount of the tensile residual stress to remain in the joint thus decreasing the fatigue resistance level, triggering a need for improvement [1], [2].

The enhancement of the fatigue resistance of welded joints is becoming increasingly significant in many areas such as the railway, aerospace and automotive industries. A recent method of enhancing the fatigue resistance of welded aluminum alloy structures is to use modern post-weld treatment processes. Improving the fatigue resistance of welded joints by conventional improvement methods such as grinding, shot peening, air hammer peening or tungsten inert gas (TIG) dressing are well established. However, these procedures are manpower intensive, not always efficient and less environmental friendly. The relatively new technique of high frequency hammer peening of weld toes as well as heat affected zones offers a favorable alternative for weld improvement. High-frequency hammer peening is termed a method in which hardened steel pins impact on the surface of the metal to be treated at a required frequency and pressure magnitude in accordance to specifications.

Rodopoulos et al. [3] investigated the outcomes of an experimental study for evaluating the effects of ultrasonic impact treatment (UIT) on the fatigue resistance of friction stir welded aluminum alloy panels. The effects of laser and shot peening on the mechanical properties with iso-stress assumption to calculate local stress–strain curves were studied by O. Hatemleh [4] for friction stir welded 2195 aluminum alloy joints. A significant improvement in the fatigue resistance of FSW AA7075 by applying ultrasonic impact peening (UIP) was reported out by Qiulin et al. [5] using a self-made device with a stress ratio of R=0.5. The strengthened layer caused by the plastic variation, surface hardening and consistency of tissue, as well as compressive transversal residual stress induced by UIP were found to be the main reasons for the increased life cycle. Microstructural and fatigue properties of FSW made of AA2043 with controlled shot peening was examined by Ali et al. [6] and stated that the compressive residual stress introduced by the peening process attributed to an increment in the low cycle region. In an attempt to restore the degraded fatigue performance due to FSW, laser peening without coating (LPwC) was applied to FSW AA6061 joints by Sano et al. [7] and obtained an increment of 30 Mpa from an as-welded value of 90 Mpa. It was pointed that a higher fatigue performance can be expected if the processing parameters in LPwC were optimized. Hence process parameter optimization is an important criterion prior to the application of any post weld treatment.

A broad development in the usage of the design of experiment (DoE) in diverse applications has been noted recently due to its capability of outlining the optimal settings of any process by determining the governing parameters associated to the process to further improve the performance and capability. A well-established example among the many statistical techniques used to reduce the number of experiments required is the Taguchi Method (TM) which enables safe identification of statistically essential parameters. Optimization in common is known as a process that permits the approximation of the most possible minimum value of process performance at the optimum point of process parameters. Numerous research involving the optimization of process parameters for FSW as well as other welding processes has been carried out previously to obtain the optimal point of governing parameters.

Employing the MTM and RSM, a mathematical model was successfully developed for quality features of resistance spot welding [8]. A hybrid Taguchi method using the Taguchi quality loss function and response surface method (TMRSM) was employed for the multi-response optimization of a laser beam cutting process [9]. TM has been successfully applied to determine the optimal FSW process parameter combination that would maximize the tensile strength, notch tensile strength and the weld nugget hardness of the AA6061 joints by Periyasamy et al. [10]. The TM was effectively used to optimize the process parameters of friction stir welding (FSW) of 6061 aluminum alloy in an attempt to minimize the heat affected zone (HAZ) distance to the weld line [11]. The prediction of the optimum tensile strength by varying process parameters for joining of a butt joint dissimilar Al–Cu alloy AA2219 and AA5083 plates using TM technique was investigated by Koilraj et al. [12].

Although numerous post weld treatments have been applied to FSW joints with an objective of increasing the fatigue strength, no attempt has been made yet to employ the recently innovated pneumatic impact treatment (PIT) which is a post weld treatment under the generic term of high frequency mechanical impact (HFMI) method as mentioned in [13]. Achieving the maximal increment in the fatigue strength using a high frequency hammer peening method such as the PIT is primarily dependent on the optimization of the PIT parameters such as the air pressure, hammering frequency and the intender pin diameter. Therefore, this research attempts to obtain the optimized parameters of PIT for FSW AA6061 joints with multi-objective outcomes, namely to achieve the highest possible fatigue life cycle and optimal hardness values.

2. Technology and function

The PIT technology is a high-frequency hammer peening process that has been developed mainly to improve the fatigue resistance of welded joints. The mechanical pulses are transmitted to the surface to be treated through hardened pins, which are adapted to the geometry of the respective application. The hand held device and PLC control unit used in the PIT process is depicted in Figure 1. In the PIT technology, both the frequency and the force of impact can be regulated independently of one another. This makes it possible to meet the varying requirements of different materials, hence each type material should be treated with the suitable process parameters accordingly to achieve the best possible results.

Figure 1. The PIT hand held device and controller with the fluidic muscle from Festo (far left).

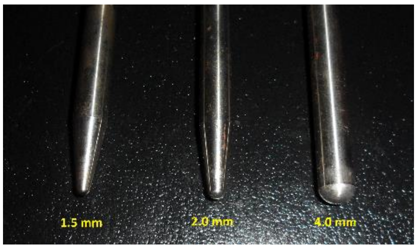

Figure 2. The PIT intender with varied pin diameters used.

The hammering frequency can be set at the control unit to 4 stages in the range of 80 – 120Hz. The parallel regulation of the air pressure within the range of 4 - 6 bar for the selected frequency allows the force of impact to be infinitely adjusted. A separate control unit with PLC controls permits entry of the treatment parameters for the various materials and different types of weld joints at a touch-screen. This makes it possible to record the treatment data over a prolonged period. The hammer pins are hardened steel pins with a diameter of 8mm and differently contoured points with varying pin diameters from 1.5mm to 4mm, depending on the treatment situation, see Figure 2. The typical treatment speed for use with aluminum materials is in the range of approximately 15 to 25 cm/min.

3. Taguchi & multi-objective Taguchi method

A Taguchi design, or an orthogonal array, is a simple and robust method of designing experiments for optimizing the governing process parameters that usually requires only a fraction of the full factorial combinations. This technique enables each factor to be independently evaluated with randomized experiments due to the orthogonal array (OA) consisting of a balanced design with equally weighted factor levels hence eliminating the possibility of one factor effecting the estimation of another factor. The ability to narrow the range of specific study or identifying problems in manufacturing process with existing data by means of emphasizing a mean performance characteristic value close to the target value rather than a value within certain specification limits has made the Taguchi method a popular choice for improving product quality [16, 17].

In a typical robust parameter design, the first step is to choose the control factors effecting the process and their levels with subsequent selection of a suitable orthogonal array for the chosen control factors while simultaneously determining a set of necessary noise factors with appropriate experimental designs. The control factors comprise the inner array while the noise factors comprise the outer array. The selection of appropriate OA is based on total degree of freedom (dof) which is computed as [17]:

$$\text{dof} = \{(a-1)\,n\} + \{(A-1) \times (B-1)\,n_i + 1\} \quad (1)$$

where a is the number of levels, n is the number of factors, and n_i is the number of interactions while A and B are the interacting control factors

In general, signal to noise (S/N) ratio (η, dB) denotes quality characteristics for the obtained data in the Taguchi design of experiments (DoE) and mathematically can be computed as [13]:

$$\eta = -10 \log [\text{MSD}] \quad (2)$$

where MSD is mean square deviation from the desired value and commonly known as quality loss function. Usually, there are three categories of the quality characteristic in the analysis of the S/N ratio which are smaller-is-better, higher-is-better and nominal-is-best. In this study the higher-is-better is and nominal-is-best is employed for fatigue life cycle and nugget zone hardness profile, whereby a the desirable magnitude of these objectives will act favorably towards achieving higher fatigue resistance properties of the joint. The MSD employing the higher-is-better and nominal is best was calculated using the following equations:

$$\text{Nominal-is-best} = \eta = -10 \log 10 \sigma^2 \quad (3)$$

$$\text{Higher-is-better} = \eta = -10[\log \left(\sum \frac{y^{\frac{1}{2}}}{\text{n}} \right)] \quad (4)$$

where y is the responses for the given factor level combination while □□□is the standard deviation and n is the number of responses in the factor level combination. Ensuing the estimation of the S/N ratio, the governing parameters with the ideal set of process parameters can be determined.

Successively analysis of the variance (ANOVA) will be employed to analyze the relative effect of the different parameters or factors. This statistical method quantitatively estimates the relative significance factors on quality characteristics [18]. A specific factor is considered to be statistically significant should the p-value is less than the significance level (α) while the F-ratio or a percentage contribution represents the significance of factors. A higher value of the F-ratio indicates a vast change on the process performance through variation of respective process parameter while p-ratio less than 0.05 the more significant will be the factor.

In multi-objective optimization, a single overall S/N ratio for all quality characteristics is computed in place of separate S/N ratios for each of the quality characteristic. This overall S/N ratio is known as multiple S/N ratio (MSNR). The MSNR for *j*th trial $\left(\eta_j^e\right)$ is computed as [17]:

$$\eta_j^e = -10 \log_{10}\left(Y_j\right) \quad (5)$$

$$Y_j = \sum_{i=1}^{k} w_i y_{ij} \quad (6)$$

$$y_{ij} = \frac{L_{ij}}{L_{i*}} \quad (7)$$

where y_j is the total normalized quality loss in *j*th trial, w_i represents the weighting factor for the *i*th quality characteristic, *k* is the total number of quality characteristics and y_{ij} is the normalized quality loss associated with the *i*th quality characteristic at the *j*th trial condition, and it varies from a minimum of zero to a maximum of 1. L_{ij} is the quality loss or MSD for the *i*th quality characteristic at the *j*th trial, and L_{i*} is the maximum quality loss for the *i*th quality characteristic among all the experimental runs.

4. Experimental design and setup

After the orthogonal array has been selected, the subsequent step in the Taguchi parameter design is running the experiment. The PIT treated friction stir welded AA6061 aluminum alloy was used in this investigation. All the welds were performed in plates rolled to 6-mm-thick pieces perpendicular to the rolling direction (RD) in a butt joint arrangement with straight edge preparation. The chemical composition of the workpiece is listed in Table 1.

Experimental process was conducted using L9 orthogonal array in Taguchi Method which has nine rows corresponding to the number of experiments as shown in Table 3. Plates of 250 mm of length and 100mm of width were cut out using a milling machine and welded along their long edge. The friction stir welding was done according to the tool dimension and optimized parameters in Mohamed et al [14]. After welding, specimens were produced by milling for fatigue tests in accordance to the specifications in ISO/TR 14345:2012(E). The specimens were then PIT treated with varied parameters, namely the air pressure, hammering frequency and intender pin diameter. The specimens were milled and then PIT treated to avoid any residual stress induced by the milling process to influence the results of the fatigue tests. The specimens for hardness measurement were PIT treated first and then cut and polished for hardness measurement.

Three PIT parameters namely the air pressure, hammering frequency and intender pin diameter were selected for experimentation with three levels of each factor. The value of the welding process parameter at the different levels is tabulated in Table 2.

Table 1. Chemical composition of workpiece

Percent Composition (%)	Si	Fe	Cu	Mn	Mg	Cr	Ni
	0.74	0.44	0.22	0.034	1.03	0.054	0.007

Table 2. Control factors and their levels used in OA design matrix

Symbol	Factors	Unit	Level 1	Level 2	Level 3
A	Air Pressure	Bar	4	5	6
B	Hammering Frequency	Hz	80	100	120
C	Intender Diameter	mm	1.5	2	4

The FSW was done on the vertical head milling machine with the position of the tool fixed relative to the surface of the sheet. The work piece was firmly clamped to the bed and a cylindrical tool was plunged into the selected area of the material sheet for sufficient time in order to plasticize around the pin. The post-weld treatment of the FSW joints using PIT technology was carried out on the finished fatigue test specimens using a PIT hand held device. The treatment was always carried out at fatigue prone areas covering the nugget zone, thermomechanical zone and heat affected zone, covering a total length of 60mm. Figure 3 shows the PIT treated surface of the FSW AA6061 butt joints with varying PIT process parameters.

Table 3. Experimental layout using L9 orthogonal array

Experiment number	Levels of factors		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The quality of the post-weld treatment was inspected visually on the basis of the contour of the treatment track to ensure the nonexistence of any remaining notch. The as-welded and post-weld treated specimens is presented in Figure 4. The overlapping of the separate pin impressions to form an almost regular track can be clearly seen.

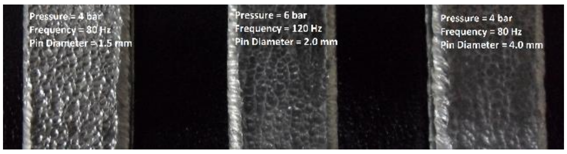

Figure 3. Treated surface of fatigue test specimens with varied PIT parameters

Before hardness tests were performed, samples for macro profiles were prepared by the usual metallurgical polishing methods and etched with Keller's reagent. The hardness field was established in the midthickness (middle level) of the cross section of the weld seam according to the ISO 6507-2 standard with 3 measured points in the nugget zone with 1kgf force using a Struers Duramin Micro-Vickers Hardness test machine.

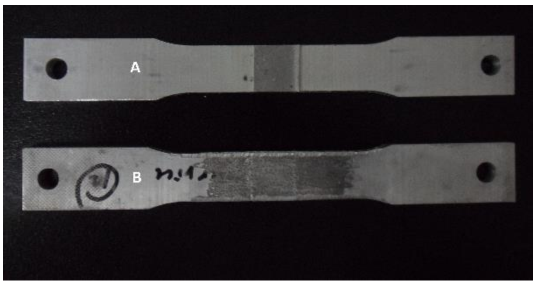

Figure 4. Fatigue test specimens as-welded (A) and with PIT treatment (B) and the length of treatment

The fatigue tests was carried out to quantify the influence of the varied PIT process parameters on the fatigue resistance of FSW AA6061 butt joints through PIT treatment. The fatigue resistance was ascertained in conventional constant amplitude fatigue tests with a constant stress ratio of R=0.1 and a frequency of 25Hz with maximum load of 120 Mpa equivalent to 70 percent of the ultimate tensile strength of the FSW AA6061 butt joint. The tests were carried out on an Instron all-purpose servo-hydraulic machine with a maximum test force of 250 kN. The tests were run without intermission until a through-going crack or a total fracture occurred. The number of load cycles from the crack initiation to a total fracture was observed to be negligibly small in relation to the total number of cycles.

5. Result and discussion

The values of the observed data for the three fatigue specimens and the average cycle to failure and Vickers hardness values are shown in the Table 4 and Table 5 respectively.

Fatigue test conducted with a stress value of 120Mpa on the PIT treated FSW AA6061 generated an overall mean fatigue strength of 272198 cycles in comparison to the as-welded FSW AA 6061 of approximately 50000 cycles [15]. The highest obtained mean fatigue life cycle of 519327 cycles is almost 10 times the fatigue resistance of the as-welded condition while the lowest recorded mean fatigue life cycle of 140444 does not depict significant improvement. The single highest recorded life cycle is 722843 which is 14 times higher than the as-welded condition. Results acquired from the number of 9 parameter variations, nearly 66 percent of the samples recorded a fatigue resistance improvement below the mean value. Notably, a lower air pressure of 4 bar resulted in a significant increment while the air pressure of 5 bar and 6 bar recorded reasonably equivalent increments. Although the hammering frequency of 80 Hz produced the highest single fatigue life cycle increment, the hammering frequency of 120 Hz produced a more constant and substantial increment while the hammering frequency of 100 Hz recorded below mean value improvements. The intender diameter of 1.5 mm generated significant enhancements to the life cycle whereas 2.0 mm and 4.0 mm generated similar fatigue strength with average improvements.

The hardness of the nugget zone were measured in center as well as in both retreating and advancing sides. It is found that the hardness of base material varies between 105 and 110 HV. Compared to the parent material, dynamic recrystallization in FSW joints plays a major role in the elimination of strain hardening which significantly softens the weld zone [1]. This in turn causes a decrement of the hardness values in the vicinity of the weld nugget. The mean hardness value of the weld nugget in the as-welded condition for FSW AA6061is recorded at 72 HV [14] compared to the average value of 95 HV obtained for the PIT treated FSW AA6061. From total number of 9 experiments, 50 percent of the hardness values attained post-PIT was comparable to the base material hardness value. It is noted that a higher value of air pressure resulted in an increment between 35-40 percent from the as-welded nugget zone hardness value. The hammering frequency of 120 Hz recorded a lower value of hardness compared to the other frequencies while the intender pin did not show any clear configuration of decrement or increment.

5.1 Multi-objective optimization results

From Table 4 and 5, quality loss values for the quality characteristics of nominal-is better and higher-is-better in each experimental run are calculated using (3) .These quality loss values are depicted in Table 6.

Table 4. Fatigue experimental results for number of cycles to failure

Experiment number	Fatigue Specimen 1 (Cycles)	Fatigue Specimen 2 (Cycles)	Fatigue Specimen 3 (Cycles)	Fatigue Mean (Cycles)
1	722843	315810	515262	517972
2	369186	289543	306196	321642
3	300397	400062	380432	360297
4	127435	152854	141042	140444
5	255926	111130	182435	183164
6	256329	178106	344877	259771
7	273845	202575	239153	238524
8	143149	173241	271152	195847
9	217819	246916	231643	232126

Table 5. Experimental results for nugget zone hardness values and weld quality class rating

Experiment number	Nugget zone hardness 1 (HV)	Nugget zone hardness 2 (HV)	Nugget zone Hardness 3 (HV)	Nugget zone mean hardness (HV)
1	98.9	96.5	97	97.5
2	84.5	94.9	85.1	88.2
3	85	87.3	84.9	85.7
4	98.4	102.4	99.4	100.1
5	105.2	106	96.7	102.6
6	86.3	92.4	95	91.2
7	98.8	102.9	101.9	101.2
8	103.4	102.1	97.4	101.0
9	91.7	92.4	85.7	89.9

The normalized quality loss values for both quality characteristics in each experimental run have been calculated using (6) that is shown in Table 7. The total normalized quality loss values (TNQL) and MSNR for multiple quality characteristics for fatigue life cycle and weld nugget hardness has been calculated using (4) and (5) respectively. These results are presented in Table 8.

In calculating the total normalized quality loss values, two unequal weights of w1 and w2 was assigned namely w1 being 0.8 for number of fatigue life cycles to failure and w2 being apportioned at a value of 0.2 for weld nugget zone hardness. Higher weighting factor has been assigned to the number of fatigue life cycles to failure rather than the weld nugget zone hardness as it is more important to achieve a favorable fatigue resistance with post weld treatment in friction stir welding process.

Table 6. Quality loss values for fatigue life cycle and nugget zone hardness

Experiment number	A	B	C	Quality loss values (dB)	
				Cycles to failure	Nugget zone hardness
1	1	1	1	5.97017E-12	1.603
2	1	2	2	9.977E-12	34.09
3	1	3	3	8.66491E-12	1.843
4	2	1	2	5.21889E-11	4.333
5	2	2	3	4.812E-11	26.56
6	2	3	1	1.83838E-11	19.94
7	3	1	3	1.83959E-11	4.57
8	3	2	1	3.1907E-11	9.963
9	3	3	2	1.87396E-11	13.56

Table 7. Normalized quality loss values

Experiment number	A	B	C	Normalized quality loss values (dB)	
				Cycles to failure	Nugget zone hardness
1	1	1	1	0.114395	0.047028
2	1	2	2	0.191171	1
3	1	3	3	0.16603	0.054067
4	2	1	2	1	0.127102
5	2	2	3	0.922036	0.779136
6	2	3	1	0.352255	0.584963
7	3	1	3	0.352487	0.134044
8	3	2	1	0.611375	0.292237
9	3	3	2	0.359072	0.397829

Table 8. Total normalized quality loss values (TNQL) and Multiple S/N ratios (MSNR)

Experiment number	A	B	C	TNQL	MSNR(dB)
1	1	1	1	0.100922	9.960147
2	1	2	2	0.352937	4.523032
3	1	3	3	0.143637	8.427329
4	2	1	2	0.82542	0.833248
5	2	2	3	0.893456	0.48927
6	2	3	1	0.398796	3.99249
7	3	1	3	0.308798	5.103254
8	3	2	1	0.547548	2.615782
9	3	3	2	0.366824	4.355428
Mean of MSNR of all experiment runs					4.4778

The effect of different control factors on MSNR is shown in Table 9. The optimum levels of different control factors for fatigue life cycles to failure and weld nugget zone hardness obtained are air pressure at level 1 (4 bar), hammering frequency at level 3 (120 Hz) and intender pin diameter at level 1 (1.5mm). ANOVA technique was further employed to detect significant factors in multi-objective optimization for fatigue life cycles to failure and weld nugget zone hardness. The result of ANOVA for the PIT treated outputs is presented in Table 10. The analysis conducted indicates that air pressure was statistically significant since its p-value is less than 0.05. Furthermore, it also shows the percentage contribution which indicates the relative power of a factor to reduce variation. For a factor with a high percentage contribution, a small variation will have a great influence on the performance [13].

Table 9. Multiple S/N response (average factor effect at different level)
* Optimum level

Symbol	Factors	Mean of multiple S/N ratio (dB)		
		Level 1	Level 2	Level 3
A	Air Pressure	17.196*	1.410	11.763
B	Hammering Frequency	10.846	5.084	14.440*
C	Intender Pin Diameter	13.447*	8.102	8.821

The percentage contribution of different control factors on multiple quality characteristics (fatigue life cycles to failure and weld nugget hardness) shows that air pressure was the major factor (66.57%), followed by hammering frequency (21.5%) and intender pin diameter (10.24%). In pneumatic impact treatment process, air pressure and hammering frequency have the greatest effect on the fatigue resistance and hardness profile.

Table 10. ANOVA result

Factors	Air Pressure	Hammering Frequency	Pin Diameter	Error	Total
DoF	2	2	2	2	8
Sum of square	52.52	16.98	8.08	1.45	78.9
Mean of square	26.26	8.49	4.0	0.72	
F	36.32	11.74	5.54		
P	0.027	0.079	0.153		
Contribution %	66.57	21.5	10.24		

5.2 Confirmation tests

The ultimate step is the validation of the optimum parameter settings suggested by the matrix through experimental verification to determine these conditions certainly produce the projected improvements. Hence, a specific combination of the factors and levels previously evaluated will be used in the confirmation experimental test. Subsequent to defining the optimal conditions, a new experiment was conducted using the determined optimum levels of governing parameters ($A_1B_3C_1$). Then the predicted value of MSNR (η_{opt}) at the optimum parameter levels was calculated by using the following equation [8]:

$$\eta_{opt} = \eta_m + \sum_{i=t}^{p} \left(\eta_{mi} - \eta_m\right) \tag{8}$$

where η_m is the mean MSNR of all experimental runs, p is the number of main welding parameters that significantly affect the performance and η_{mi} is the average MSNR at the optimal level.

The predicted value of MSNR and that confirmation experiment is shown in Table 11. This verification depicts an improvement in multiple S/N ratio of 3.0796 dB upon the alteration of the initial governing parameter setting of $A_2B_2C_3$ to the optimal setting of $A_1B_3C_1$. Since this was the inaugural attempt to apply the PIT on FSW AA6061 butt joints, the initial parameters was chosen based on a trial-mode to use a moderate air pressure and hammering frequency combined with a large intender pin diameter to obtain the required fatigue life enhancement. The outcomes shows reasonable improvement in both outcomes, namely the fatigue life cycle and the nugget hardness values with the multi-response optimization used as compared to the initial values of the fatigue life cycles and nugget hardness values obtained.

Table 11. Result of the confirmation experiment

	Initial parameter setting	Optimal process parameters	
		Prediction	Experiment
Level	$A_2B_2C_3$	$A_1B_3C_1$	$A_1B_3C_1$
Fatigue life cycle (N)	183164	652843	688626
Nugget hardness (HV)	102.6	104.5	105
Multiple S/N ratio (dB)	0.605818	3.5843	3.68543
Improvement in multiple S/N ratio = 3.0796 dB			

The fatigue resistance shows significant changes with improvement from the initial enhancement of 3 times to a 12 times increment of fatigue strength improvement from the untreated specimens. The nugget zone hardness values shows reasonable values. Overall, a good agreement is seen in the predicted and experimental results obtained for both fatigue life cycle and nugget zone hardness values.

6. Conclusion

A multi-objective optimization has been applied with simultaneous consideration of multiple response (fatigue life cycle and hardness profile) using Taguchi Method to optimize the multiple quality characteristics in high frequency hammer peening process. Based on the optimization and modelling results, the following conclusions can be drawn:

(1) The multiple characteristic such as fatigue life cycle and hardness profile can be simultaneously considered using multi-objective Taguchi Method

(2) The role of different control factors is air pressure (66.57%), hammering frequency (21.5%) and intender pin diameter (10.24%). The air pressure plays a major role in determining reasonable surface hardening and superior fatigue life cycle in FSW joint.

(3) The optimum parameters for a higher fatigue life cycle and hardness is: air pressure at level 1 (4 bar), frequency at level 3 (120 Hz) and intender diameter at level 1 (1.5 mm)

(4) The PIT process parameter optimization is significant due to the fact that each variation instigates an improvement between 3 to 14 times, hence the wrong process parameter may deteriorate the maximum possible fatigue enhancement.

(5) PIT treatment is a post weld treatment that can be used to significantly enhance the fatigue resistance level of FSW AA6061.

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